

Enhanced Tensile Behavior of Epoxy Nanocomposites Reinforced with Multi-Walled Carbon Nanotubes via Dual-Action Dispersion Technique

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Abstract

This study explores the effect of multi-walled carbon nanotube (MWCNT) reinforcement on the tensile properties of epoxy nanocomposites, using a hybrid dispersion technique involving ultrasonic cavitation and shear force from an axial-flow impeller. Various loadings of MWCNTs (0.25 wt% to 1.0 wt%) were incorporated into the epoxy resin, and the resulting mechanical behavior was evaluated. Optimal performance was observed at 0.75 wt% MWCNTs, with tensile strength and toughness increasing by 36% and 53%, respectively, compared to unfilled epoxy. Scanning electron microscopy of fractured surfaces revealed effective dispersion and crack-arresting mechanisms at intermediate filler concentrations, while higher loadings led to agglomeration and property deterioration. The findings confirm that dispersion quality and interfacial interaction are crucial factors in achieving mechanical enhancement in CNT-reinforced epoxy systems.

Keywords

MWCNT, Mechanical Behavior, Electron Microscopy

1. Introduction

Epoxy-based composites reinforced with carbon nanomaterials have emerged as promising materials for advanced structural applications due to their potential to

offer a unique combination of strength, stiffness, and durability [1]-[3]. Among various nanofillers, multi-walled carbon nanotubes (MWCNTs) are particularly attractive owing to their high aspect ratio, outstanding tensile strength, and excellent load transfer capability [4]-[6].

Despite these advantages, the full mechanical potential of MWCNT-reinforced epoxy nanocomposites often remains underutilized due to challenges in achieving homogeneous dispersion and robust interfacial bonding between nanotubes and the matrix [7]-[9]. Agglomeration of nanotubes, driven by van der Waals interactions, can act as stress concentrators and lead to premature failure, counteracting the expected reinforcement [10].

Several dispersion techniques, such as ultrasonication, shear mixing, and calendaring, have been employed to address these challenges [11]-[14]. However, relying on a single method often fails to deliver both thorough deagglomeration and uniform matrix incorporation. This study addresses this issue by utilizing a dual-action dispersion technique that synergizes ultrasonic energy and axial shear flow, aiming to optimize the mechanical performance of MWCNT/epoxy nanocomposites.

Focusing exclusively on tensile performance, this work investigates how different MWCNT loadings influence the mechanical strength and toughness of the composite. It highlights the role of nanotube dispersion and microstructural characteristics in dictating macroscopic tensile behavior.

2. Materials and Methods

2.1. Materials Used

The matrix material used in this study was a commercial-grade epoxy resin (Cam Coat 2071), paired with an aliphatic hardener, both procured from Champion Advanced Materials Pvt. Ltd., India. The reinforcing agent—multi-walled carbon nanotubes (MWCNTs)—was synthesized using the chemical vapor deposition (CVD) technique and had an average diameter of approximately 30 nanometers.

2.2. Composite Preparation

To prepare the nanocomposites, various weight fractions of MWCNTs (0.25, 0.50, 0.75, and 1.0 wt%) were incorporated into the epoxy resin. Initially, the MWCNTs were dispersed in the epoxy matrix with the aid of 10% acetone, used as a temporary diluent to reduce viscosity and facilitate uniform blending. Preliminary mixing was carried out manually using a glass rod.

For refined dispersion, a combined method involving ultrasonication and mechanical shear was employed. A titanium alloy probe (13 mm diameter) operating at 20 kHz and 750 W output delivered ultrasonic energy, while an axial-flow impeller running at 400 rpm introduced shear forces to the system. The ultrasonic tip was strategically positioned at the periphery of the mixing vortex to enhance the deagglomeration of MWCNT clusters via repeated cavitation. Pulsed sonication (10 seconds on, 10 seconds off) was applied for 30 minutes at 60% ampli-

tude. An external cooling system was used to limit the processing temperature below 45°C.

Following dispersion, the acetone was allowed to fully evaporate. The curing agent (10 wt% of the resin weight) was then blended thoroughly into the mixture. This formulation was subjected to vacuum degassing to eliminate air bubbles before being cast into silicone rubber molds. The filled molds were placed in a hot air oven at 50°C for 12 hours to complete the curing process.

2.3. Mechanical Testing

Tensile properties were assessed using standard dumbbell-shaped specimens prepared according to ASTM D638 guidelines. A universal testing machine was used to perform the tensile tests at a crosshead speed of 1 mm/min. The ultimate tensile strength was determined from the maximum load, while the area under the stress–strain curve was computed to quantify toughness.

2.4. Fracture Surface Examination

To investigate the dispersion of nanotubes and failure mechanisms, the fracture surfaces of tensile specimens were examined using field emission scanning electron microscopy (FESEM). The samples were sputter-coated with a thin layer of gold and imaged at an accelerating voltage of 15 kV.

3. Results and Discussion

3.1. Tensile Performance of Nanocomposites

The mechanical response of the MWCNT-reinforced epoxy composites was systematically analyzed through tensile testing, with results summarized in **Figure 1** and **Figure 2**. The incorporation of MWCNTs notably influenced the tensile strength and toughness of the epoxy matrix.

As the MWCNT content increased from 0 to 0.75 wt%, a clear upward trend in tensile strength was observed. The 0.75 wt% composite exhibited the most substantial enhancement—approximately 36% higher strength compared to neat epoxy. This improvement is attributed to the effective stress transfer between the matrix and well-dispersed nanotubes, enabled by strong interfacial interactions and a percolated nanotube network.

Toughness, estimated from the area under the stress–strain curve, also followed a similar pattern. The toughness of the 0.75 wt% composite increased by over 50%, indicating improved resistance to crack initiation and propagation. These findings suggest that MWCNTs serve as microstructural barriers that deflect or blunt advancing cracks, thereby enhancing energy absorption during fracture.

However, at 1.0 wt% loading, a slight decline in both tensile strength and toughness was recorded. This reduction is attributed to nanotube agglomeration at higher concentrations, which leads to stress concentration sites and inefficient load transfer. Such agglomerates act as micro-defects, undermining the mechanical integrity of the composite. Similar saturation effects at higher filler loadings

have been reported in CNT-reinforced systems [1]-[3].

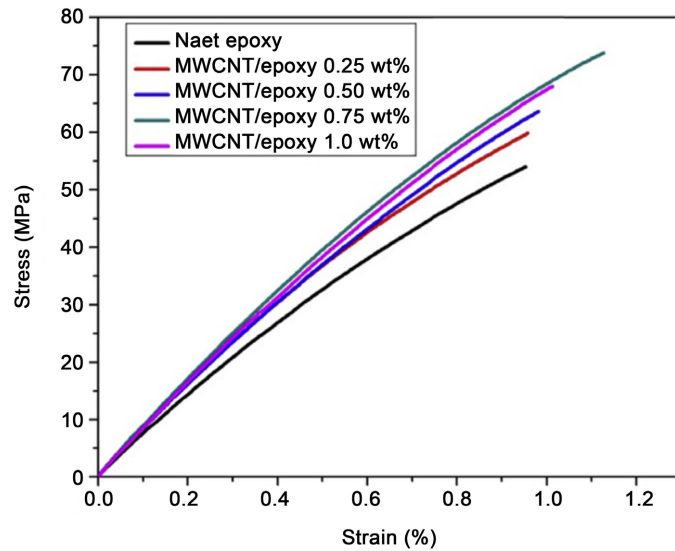


Figure 1. Stress-strain curves of neat epoxy and MWCNT/epoxy nanocomposites at various MWCNT loadings (0.25 wt%, 0.50 wt%, 0.75 wt%, and 1.00 wt%). The 0.75 wt% sample shows the highest tensile strength and deformation capacity.

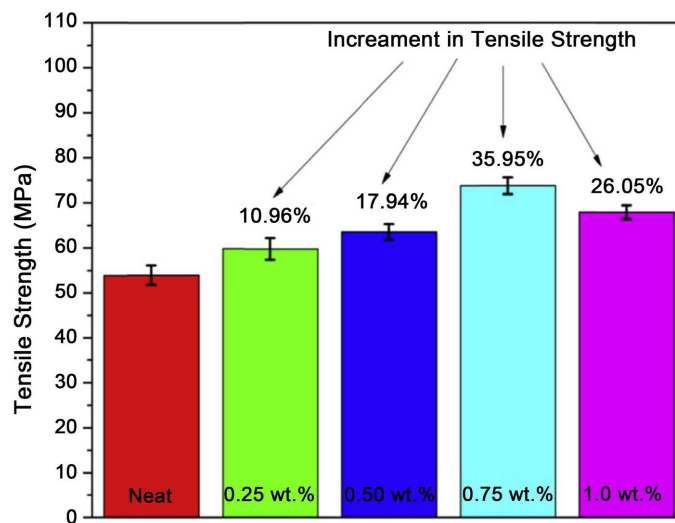


Figure 2. Tensile strength and toughness of epoxy nanocomposites as a function of MWCNT content. Peak performance is observed at 0.75 wt%, followed by a decline at 1.00 wt% due to nanotube agglomeration.

3.2. Fractographic Analysis

To validate the tensile data and understand the failure mechanisms, FESEM was employed to examine the fractured surfaces of representative samples. As shown in **Figure 3**, neat epoxy exhibited a relatively smooth and featureless fracture surface, typical of brittle failure with limited energy dissipation.

With the addition of MWCNTs, the morphology transitioned significantly. The 0.25 wt% and 0.50 wt% composites showed increasingly rough and tortuous sur-

faces, with signs of matrix tearing and nanotube pull-out. These features suggest improved plastic deformation and energy absorption during fracture.

The 0.75 wt% sample displayed the most complex fracture morphology, characterized by multi-directional crack patterns, stretched fibrils, and embedded nanotubes—evidence of strong filler-matrix interaction and effective mechanical reinforcement.

In contrast, the 1.0 wt% specimen exhibited localized nanotube clusters and smoother failure zones, consistent with premature fracture due to weak interfacial bonding and insufficient dispersion. These observations confirm that uniform dispersion is critical for maximizing reinforcement efficiency in CNT-based composites [4]-[6].

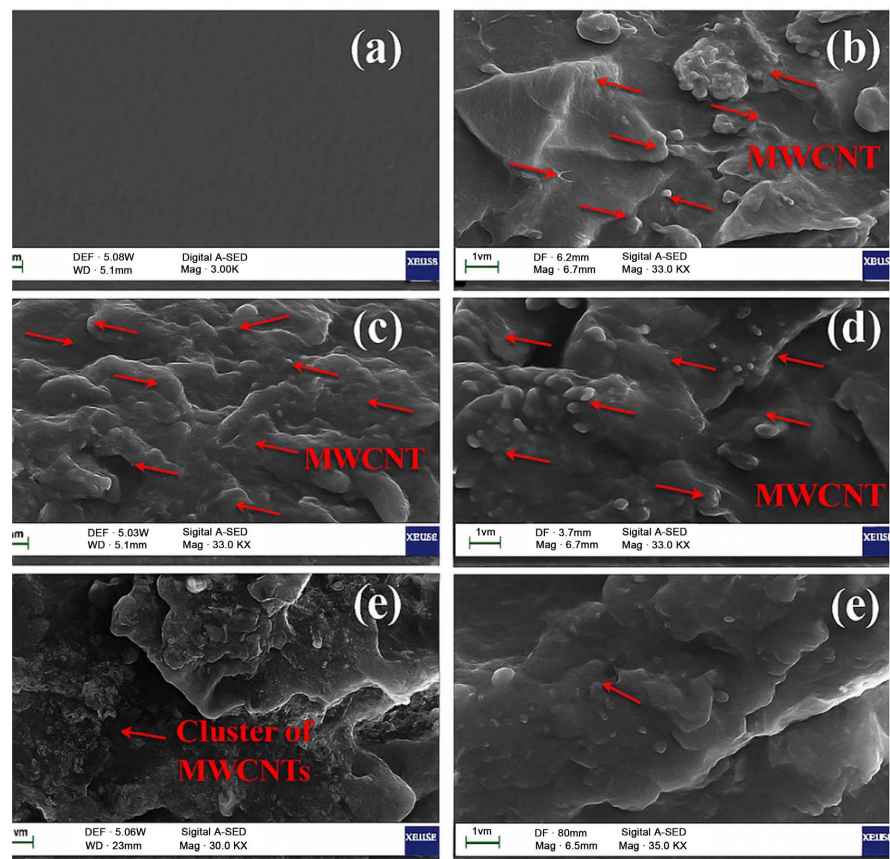


Figure 3. FESEM images of fracture surfaces of (a) neat epoxy, (b) 0.25 wt% MWCNT/epoxy, (c) 0.50 wt% MWCNT/epoxy, (d) 0.75 wt% MWCNT/epoxy, and (e) 1.00 wt% MWCNT/epoxy. Increasing roughness and nanotube involvement are evident up to 0.75 wt%, while agglomerates appear at 1.00 wt%, correlating with the decline in mechanical performance.

4. Conclusions

This study demonstrates that the tensile performance of epoxy nanocomposites can be significantly enhanced through the incorporation of multi-walled carbon nanotubes (MWCNTs) using a dual-mode dispersion strategy combining ultra-

sonication and shear mixing. Among the different loadings tested, the composite with 0.75 wt% MWCNTs exhibited optimal mechanical performance, achieving a 36% increase in tensile strength and a 53% improvement in toughness compared to neat epoxy.

The improvement is attributed to the uniform distribution of MWCNTs, which enables efficient load transfer, crack deflection, and energy absorption. Field emission scanning electron microscopy revealed a clear transition from brittle to ductile fracture modes with increasing nanotube content, further supporting the mechanical findings.

However, excessive MWCNT content (1.0 wt%) led to agglomeration, which compromised interfacial bonding and introduced defects that reduced the reinforcing effect. These results emphasize the importance of achieving and maintaining homogeneous dispersion to fully exploit the reinforcing potential of MWCNTs in thermosetting polymer systems.

The proposed processing method offers a scalable route for fabricating high-performance epoxy nanocomposites suitable for structural applications requiring improved mechanical robustness.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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